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A THEORETICAL CALCULATION OF RAPID X-RAY TRANSIENTS AND RADIUS EXPANSION*

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ABSTRACT

We present a calculation of a thermonuclear runaway on a 10 km neutron star which produces two x-ray bursts separated by ~ 2500 sec.

INTRODUCTION

In an exciting review talk given at this workshop Lewin (1983, these proceedings) presented and discussed the existence of rapid transient x-ray events with a precursor. He speculated that these events represented rapid expansion and contraction of a photosphere on a neutron star caused by a thermonuclear runaway in the accreted envelope on the neutron star. It is the purpose of this paper to show that a thermonuclear runaway in a thick accreted envelope on a neutron star will, indeed, cause a rapid expansion of the envelope to at least 10^2 km and, thereby, produce two x-ray events separated by a short time interval. In fact, the calculations to be discussed in this paper have already appeared[1,2] although the correspondence between theory and observations was not emphasized in these papers.

The specific events discussed by Lewin (1983, these proceedings) were originally presented by Hoffman _et al._[3] and will not be discussed here.

EVOLUTIONARY RESULTS

The two studies are similar enough so that we will concentrate only on our own[1] (hereafter SKST). We evolved a thermonuclear run-

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away in the accreted hydrogen-rich envelope of a $1.0M_\odot$ neutron star with a radius of 10 km. We assumed that the luminosity of the neutron star was low and that the rate of mass accretion was small enough so that a thick envelope could exist before the runaway began. More details and a discussion of these assumptions can be found in SKST or Wallace, Woosley, and Weaver.[2] In this paper we concentrate on the time after the sharp rise in the light curve caused by the breakout of a shockwave at the surface. Although this spike is described as a precursor in SKST, it is much too short to be the precursor observed by Hoffman et al.[3] or discussed by Lewin in his review. However, the point to be presented in this paper is that there were two more times during the evolution when the simulation produced x-ray burst behavior and these two events were separated by $\sim$ 2700 sec in excellent agreement with the observations.

Once shock breakout has occurred the surface layers respond with a rapid increase and decrease in both radius and luminosity. The continuing release of energy in the interior produces a second rise in luminosity and effective temperature. This second rise takes 1.4×10^{-3} sec to reach a peak luminosity of 2.75×10^{38} erg sec^{-1} at an effective temperature of 2.4×10^7K (kT $\sim$ 2.1 kev). The outer radius of the neutron star now begins to expand and as it expands both the luminosity and the effective temperature decrease. After 6.2 sec of expansion, the luminosity has dropped to 8.5×10^{37} erg sec^{-1} and the effective temperature has dropped to below $\sim$ 0.5 kev. By this time the photospheric radius of the neutron star has reached to 200 km and is still expanding. Over the 6 second interval of this event, one would have detected an initially hard spectrum followed by a rapid softening. The light curve for this part of the evolution is shown as Figure 6b in SKST.

For the next 2500 seconds, the neutron star is emitting at an average rate of $\sim 2 \times 10^{38}$ erg/sec, but its radius is $\sim 2 \times 10^3$ km and so its effective temperature is $\sim$ 0.2 kev and presumably undetectable by the SAS-3 satellite. In addition, we would expect to have a wind and mass loss produced as a result of this evolution. The intense nuclear energy generation finally causes most of the CNO catalytic nuclei to evolve to higher mass nuclei[4] and the rate of energy generation begins to decline causing the surface of the star to shrink. As it shrinks, gravitational energy is released and the surface becomes hotter and the luminosity increases. It slowly climbs above $\sim$ 1. kev and the third and last x-ray event begins.

The final x-ray event takes $\sim$ 21 sec to reach a maximum luminosity of 3×10^{38} erg sec^{-1} and a maximum effective temperature of 2.5×10^7 K (kT $\sim$ 2.2 kev). Unlike the previous event, this one starts soft and gets harder as it approaches maximum. The peak in both luminosity and effective temperature occurs when the radius has shrunk back to 10 km and the final decline to invisibility takes another 10 to 20 sec. While this seems too short to agree with the observations, in an actual outburst a wind would have been produced and the photosphere would have been receding inward through the outflowing gas during the last stages of the outburst. Such a stage is analogous to the last stages of the nova outburst[5] where the material which forms the photosphere is much hotter than the gas at the edge of the outflow. Therefore, in an actual event we would predict that the final x-ray burst would start earlier and last longer than in our simulation.

CONCLUSIONS

These calculations and those of Wallace, Woosley, and Weaver,[2] both done using a hydrodynamic computer code, show that thermonuclear runaways in thick accreted envelopes on neutron stars will produce precursors, radius expansion, mass loss from stellar winds, and a final x-ray burst analogous to that observed by Hoffman, *et al.*[3]

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